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A Handbook of Flight Simulation Fidelity Requirements for Human Factors Research

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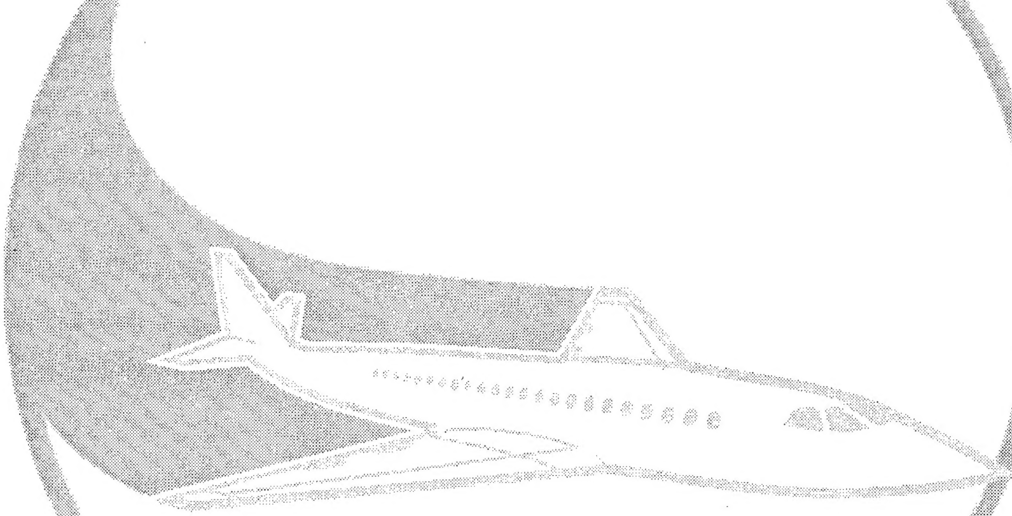

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16. Abstract

This report examines relevant literature for guidelines relative to the use of flight simulators, ranging from full mission to part-task trainers, in addition to requirements for flight crew experience and qualifications. Both sets of guidelines are established based on human factors research requirements, and are intended to match those requirements with the level of effort in establishing a test bed. In particular, researchers are provided guidance in choosing the minimum required test bed sophistication to achieve the objectives of a research program.

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FOREWORD

This report documents work performed by Crew System Ergonomics Information Analysis Center (CSERIAC) on Subtask 2 of the task entitled "Simulation Fidelity Requirements." The task was a provision of an Interagency Agreement between the Federal Aviation Administration Technical Center (Department of Transportation) and the Defense Technical Information Center (DTIC). It was conducted under DOD Contract Number DLA900-88-D-0393, and the CSERIAC Task Number was 93956-24. The CSERIAC Program Manager was Mr. Don Dreesbach. The CSERIAC Task Leader was Mr. Michael C. Reynolds. The Federal Aviation Administration Technical Program Manager (TPM) was Mr. Albert J. Rehmann, and the FAA project engineer was Mr. Pocholo Bravo.

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EXECUTIVE SUMMARY

This document investigates the issue of fidelity and the role it plays in choosing the appropriate simulation device for flight deck human factors research. Fidelity is concerned with the degree to which a flight simulator matches the characteristics of the real airplane. An extensive search of the scientific literature provided the most current information related to simulator fidelity and how to determine what levels of fidelity are necessary for simulated experimental research. The purpose of this report is to provide basis material to guide the Federal Aviation Administration (FAA) in stipulating the simulator sophistication (level of fidelity) required to conduct various types of flight deck experimental research.

This analysis defines a research simulation device and identifies the three general categories of aircraft simulation devices: (1) airplane simulators, (2) airplane flight training devices, and (3) computer-based simulation devices. The use of simulation is an extremely important resource for most aviation human factors research and development programs. This importance is due to a variety of factors, including cost and time savings that can be realized, the ability to reproduce and examine situations that would be unsafe using actual equipment, and the control and measurement of human-machine performance. Simulation provides an early opportunity to bring experienced flight crews into the aviation human factors design process to assess and insure, in particular, proper man/machine interfaces and workload levels.

Additional impetus has been provided by the tremendous technological advances in computer software and hardware capabilities being incorporated into these devices. These robust capabilities are being obtained at the expense of increased developmental, operational, and maintenance costs. This increased cost has caused flight simulator users to look closely at the simulator requirements necessary to effectively perform their tasks, and then invest enough resources to obtain a simulation device that meets their specified needs. Failure to properly determine these simulator requirements can result in (1) unsatisfactory results due to lack of realism, or (2) satisfactory results but at premium cost (suboptimization).

Before deciding what simulation requirements are necessary for a specific need, researchers need to understand simulator effectiveness and the concept used to describe it, fidelity. The concept of fidelity relates to the degree to which the characteristics of a flight simulator match those of the actual airplane. Simulator fidelity has been discussed and studied for over 30 years, and there is still no agreed upon single definition. During this time, the term has been used in a variety of ways and to refer to many different aspects of simulation. A representative sample of the different kinds of fidelity includes such things as: equipment fidelity, environmental fidelity, psychological fidelity, task fidelity,

physical fidelity, and functional fidelity. A common thread, however, is that together these definitions imply at least two major features or dimensions along which these simulated devices may differ from actual equipment.

These two features represent the division of a simulator into two classes depending on the nature of the cues they provide.

1. Equipment cues provide a duplication of the appearance and feel of the operational equipment (the aircraft), i.e., the static and internal dynamic characteristics such as the size, shape, location, and color of controls and displays, including controller force and displacement characteristics.

2. Environment cues provide a duplication of the environment and motion through the environment. Fidelity is then a function of the degree to which the equipment and environmental cues relate to those of the real airplane.

Among the two major categories of simulators, training and research, there is a tradeoff between equipment and environmental cue fidelity required. The physical correspondence between simulator and airplane in terms of cockpit layout, flight instruments, controls, etc., for training simulators should result in high equipment cue fidelity to advocate a high degree of transfer of training to the operational environment. On the other hand, research and development simulators should place more emphasis on high environmental cue fidelity. Environmental cues, by definition, provide duplication of the operational aircraft environment and motion, and thus will result in a higher degree of realism being experienced by the subjects. This perceived realism will result in subject performance more closely matching that which would occur in the real world.

Once the concept of fidelity and its effect on simulation is understood, requirements for simulation experimental research can be examined. The essential feature of simulator experimental investigations is to introduce the pilots into a closed loop control situation, so that account is taken of their capabilities and limitations regarding the performance or behavior being evaluated. The expectation is that within the bounds of the experimental conditions, behavior in the simulator will match their behavior in the flight situation. Hence, the primary goal for a flight simulation researcher is to produce experimental conditions that elicit behavior that would occur under similar circumstances in the real world. However, regardless of the level of fidelity and how accurately it was determined to meet the goals of the research, no simulator evaluation can completely duplicate the experience in the real world. Therefore, any results should be verified operationally before definite conclusions can be made.

When planning human factors research, the required characteristics and features of the research vehicle are

prominent issues of consideration in the goal of choosing the right simulator for the planned research investigation. Two principal factors in determining the choice of research vehicle are (1) the type of research required by the problem, and (2) knowledge of the factors that influence the behavioral processes of interest. The type of research dictates the level of representation that the research vehicle must have. Knowledge of the factors which influence the behavioral processes determine how comprehensively the research vehicle must represent an operational system and its associated situational condition. Together, these features are commonly thought of as the fidelity of the research vehicle.

Simulation researchers are faced with the many problems, considerations, and conflicting issues relating to the determination of fidelity requirements for a simulation research effort. Fidelity is a multivariant construct with no consensus among researchers of a single index of measurement or definition. Given the degree of differences and difficulties relating to simulator fidelity, specific guidelines for various types of experimental research are not presently available. However, general conclusions can be made regarding how varying levels of fidelity can effect the outcome of different types of experiments. Experimental research studies performed using a simulation device generally fall into two categories, full-mission and part-task. Full-mission studies examine behavior in the full context of the aviation environment, while part-task studies concentrate on the behavior relating to a specific task or function. Within these two categories there are distinct study types that are distinguished by the complexity of their objectives or the type of simulation device used for investigation.

The basic idea of full-mission relates to performing a research study with the most realistic simulation possible. It includes the aircraft cockpit, visual and motion cues, aircraft flight dynamics, all of the aircraft subsystems, the flight environment (including air traffic control, weather, and other air or ground vehicular traffic), the cabin crew, and all ancillary flight services (such as dispatch, ramp passenger services, and maintenance). Given these characteristics of full-mission simulation, it can be accurately stated that only airplane simulators should be used for full-mission simulation applications. The airplane simulators are the only simulation devices that specify visual and motion characteristics by definition, and these capabilities are definitely necessary when conducting full-mission simulation research. A full-mission simulation can be used to investigate cognitive tasks in the context of the multitask, complex operation of flying an airplane. Also, much of the research performed using full-mission simulation focuses on cockpit instrumentation, crew procedures, and workload measurement.

A main fidelity issue of concern in full-mission simulation is the pilot subjects' desire for scenario fidelity. Pilots generally do not accept deviations from operational practice unless it is specified at the beginning of the simulation. Pilots experiencing negative user acceptance cues are more likely not to elicit the same behavior as they might in the real world. Hence, for full-mission simulation research studies, the higher the level of fidelity the more likely their behavior will represent that of the operational environment and therefore be generalizable to the real world.

The concept of a part-task study is to investigate a performance measure in response to a specific manipulated task or function. These types of investigations isolate a single critical function for evaluation in terms of pilot behavior. The benefit of part-task simulation is derived from the view that the evaluation of smaller component tasks is more acceptable for experimental testing and statistical analysis and more objective information regarding performance can be obtained. Basically, studies looking at human performance on a specific individual task (reaction time, accuracy, etc.), or functional problems inherent to a task or condition can be evaluated using part-task simulation. However, what part-task simulation may gain in experimental control it lacks in external validity, i.e., accurate representation of the real world.

Part-task simulations can utilize a wide variety of simulation devices such as: microcomputer simulation devices, low-fidelity desktop training devices, and high fidelity airplane flight training devices. This wide range of fidelity devices complicates the issue of determining specific requirements for part-task simulation fidelity. The utilization of too much fidelity can result in unwanted variance associated to the behavior being examined. On the other hand, if the simulation does not represent the context in which the specific task is to be investigated, due to a low level of fidelity, the behavior examined may not be exactly that for which the research was intended. Hence, fidelity requirements for part-task simulation studies cannot be determined in general. The requirements must be determined on a case-by-case basis depending on the objectives of the research.

In conclusion, simulation fidelity is an obscure concept that is being thrust onto the simulation community as a way to measure a simulation device's effectiveness for human factors research. To date, no consensus on just what exactly fidelity is, or how it affects simulation research efforts has been reached. Additionally, the amount of research available that investigates fidelity requirements for research simulators is not abundant, and no real guidelines have ever been agreed upon by simulator researchers. To reiterate, simulation fidelity requirements are dependent specifically on what the simulator is to be used for. A well-designed research simulation project is cost-effective when compared to most other ways of achieving the same

objectives, such as flight test. However, as the use of simulation for research increases, more specific guidelines and requirements for fidelity are necessary to ensure that the simulation devices are being used effectively to meet the objectives of the specified research. Recommendations for future research to provide more specific requirements for human factors simulation research are presented at the end of the document.

1. INTRODUCTION.

Flight simulation is a vital part of aeronautical research. This research is conducted on a broad front, both at research establishments and in industry. Simulation ranges from comprehensive representations of the operational equipment and environment in support of full-mission performance to modest simulations involving a single item of equipment or part task. Simulation allows researchers to combine real-world hardware, environmental conditions, and task demands with the ability to control events and conditions. Also, research simulators allow designers to explore the implications of different design options without having to incur the expense and delay arising from building and testing a range of prototypes. In addition, flight simulation research has provided a means of evaluating the likely behavior and consequences arising from abnormal operating configurations without jeopardizing the safety of the flight crews. Ultimately, the use of simulation will result in data being collected faster and more economically than in the real world.

The use of flight simulation in research has extended considerably in the last 20 years, as equipment improvements have become available. As this growth continues, there are many issues that are being debated regarding the use of simulation for experimental research and development. One of the major issues surrounding human factors flight simulation research involves determining what level of simulator fidelity is necessary to provide satisfactory experimental results.

One group among today's heavy users of flight simulators continues to strive for as much realism as possible, i.e., (high fidelity). The belief here is that the more realistic a simulation is perceived by the pilots, the more their behavior mimics that in the operational environment. Technology advancements have made the goal of a motion-based simulator with a wraparound visual system and the exact duplication of every detail of the cockpit a reality. The high degree of cockpit similarity in this type of simulator conveys a high degree of face fidelity, or overall representation of real-world characteristics. This face fidelity has played a major role in gaining acceptance from professional pilots for using simulators to conduct experimental research. Be this as it may, with the ever-increasing use of flight simulators and their expanding costs, other groups in the simulation research community have long supported the use of lower levels of fidelity depending on the goal of the simulation.

The work described herein analyzes simulator fidelity issues and discusses fidelity requirements for human factors simulation research studies. An extensive literature review was performed on the general topic of research simulator fidelity issues. This topic was investigated to provide guidance information for the Federal Aviation Administration (FAA) to consider when

determining fidelity requirements for specific types of human factors experimental research studies. The general concept of fidelity will be introduced and issues concerning various levels of fidelity in simulation research are summarized.

1.1 PURPOSE/SCOPE.

The information contained herein provides a handbook to guide the FAA in selecting experimental apparatus as a function of a given research study. This handbook will support the FAA's future flight deck data link human factors research program that utilized their established Cockpit Simulator Network (CSN). Material found in this handbook discusses how to utilize resources (simulators) in the most efficient (technically) and cost effective way, given that as fidelity increases, cost increases. Issues regarding necessary simulator fidelity requirements for conducting human factors research are addressed.

1.2 ORGANIZATION OF THE REPORT.

The report will begin with a brief introduction to the various types of research simulation devices and proceeds to classify them into three major categories based on their characteristics. The categories are (1) Airplane Simulator, (2) Airplane Flight Training Device, and (3) Computer-Based Simulation Device. Next, the term "Fidelity" is defined with regards to simulation and the individual components that drive varying levels of fidelity are discussed in detail. The following section examines research simulator fidelity requirements in general, and discusses the conflicting trains of thought in the simulation community regarding the level of fidelity necessary to obtain significant results. The fourth section examines general fidelity requirements for research simulators and discusses the advantages and corresponding disadvantages associated with different levels of simulator fidelity.

The last major section (Human Factors Research Fidelity Concerns) looks at the fidelity characteristics of the two main types of human factors simulation research, full-mission and part-task, and examines what type of performance measures should be evaluated in each. Also, the type of simulation devices to be utilized for conducting full-mission and part-task simulation research are discussed. Furthermore, recommendations for specific types of simulation devices that can be used for various research objectives is provided in this section. Finally, the last section of the report will provide recommendations for future research to further investigate the construct of fidelity and its significance and influence on conducting human factors simulation research studies.

2. SIMULATED EXPERIMENTAL RESEARCH DEVICES.

The use of simulation is an extremely important resource for most aviation human factors research and development programs.

Simulation provides an early opportunity to bring experienced flight crews into the aviation human factors design process to assess and insure, in particular, proper man/machine interfaces and workload levels. In this manner these flight crews are able to contribute to control system design and flight deck layout and to the integration/operation of complex subsystems, like an integrated Flight Management System (FMS). Also, research and development simulators can provide a means of evaluating the likely behavior and consequences arising from abnormal operating configurations.

In terms of equipment, research and development simulated devices run the full spectrum from computer-based flight simulators, to desktop part-task simulators, and ultimately to full-mission, 6 Degrees of Freedom (DOF) flight simulators with full out-the-window visual systems. The ever-increasing emphasis on the utility of research and development devices is evident by the significant increase of this type of equipment appearing across the world in government laboratories, universities, and civilian industries.

Aviation simulation used for research includes numerous different types of devices distinguished by technical capabilities and capital investment required. For this analysis of fidelity requirements, three categories will be defined to encompass all aviation simulated research devices: (1) Airplane Simulator, (2) Airplane Flight Training Device, and (3) Computer-Based Simulator. Throughout the remainder of this document, the general term "simulator" will be used to refer to all three categories of simulation devices, unless otherwise specified. Within these broad categories of devices there is further distinction based on their associated level of objective fidelity (physical realism to the real world). For example, the FAA has published two separate FAA Advisory Circulars (AC), FAA-AC-120-40B and FAA-AC-120-45A, that contain training qualification requirements for airplane simulators and airplane flight training devices, respectively, and classify these devices in terms of objective fidelity. Simulator classification by objective fidelity sets a basis from which the training community can identify the specific simulation device that is optimized for their needs (Prasad, et al., 1991). A definition and detailed description of the various levels of simulation capability for each category of simulation device is described below.

2.1 AIRPLANE SIMULATOR.

An airplane simulator is a full size replica of a specific type of make, model, and series airplane cockpit (e.g., Boeing 727-200 or MD-80-20), including the assemblage of equipment and computer software programs necessary to represent the airplane in ground and flight operations, a visual system providing an out-of-the-cockpit view, a force (motion) cueing system which provides cues at least equivalent to that of a 3 DOF motion system; and is in compliance with the minimum standards specified in FAA Advisory

Circular 120-40B, as amended in July 1991. A functional description for each of the four levels of airplane simulators are given below. Differences in each simulator's description, as the level of sophistication increases from Level A to Level D, are listed below.

Level A Flight Simulator

Functional Description

a. Systems representations, switches, and controls which are required by the type.

b. Design of the aircraft and by the user's approved training program.

c. Systems which respond appropriately and accurately to the switches and controls of the aircraft being simulated.

d. Full-scale replication of the cockpit of the aircraft being simulated.

e. Correct simulation of the aerodynamic characteristics of the aircraft being simulated.

f. Correct simulation of the effects of the selected environmental conditions which the simulated aircraft might encounter.

g. Control forces and travel which correspond to the aircraft.

h. Instructor controls and seat.

i. At least a night visual system with at least a 45° horizontal by 30° vertical field of view for each pilot station.

j. A motion system with at least 3 DOF.

Level B Flight Simulator

Functional Description

a. Systems representations, switches, and controls which are required by the type design of the aircraft and by the user's approved training program.

b. Systems which respond appropriately and accurately to the switches and controls of the aircraft being simulated.

c. Full-scale replication of the cockpit of the aircraft being simulated.

d. Correct simulation of the aerodynamic characteristics including ground effect, and ground dynamic characteristics of the aircraft being simulated.

e. Correct simulation of the effects of the selected environmental conditions which the simulated aircraft might encounter.

f. Control forces and travel which correspond to the aircraft.

g. Instructor controls and seat.

h. At least a night visual system with at least a 45° horizontal by 30° vertical field of view for each pilot station.

I. A motion system with at least 3 DOF.

Level C Flight Simulator

Functional Description

a. Systems representations, switches, and controls which are required by the type.

b. Design of the aircraft and by the user's approved training program.

c. Systems which respond appropriately and accurately to the switches and controls of the aircraft being simulated.

d. Full-scale replication of the cockpit of the aircraft being simulated.

e. Correct simulation of the aerodynamic characteristics including ground effect, and ground dynamic characteristics of the aircraft being simulated.

f. Correct simulation of the effects of the selected environmental conditions which the simulated aircraft might encounter.

g. Control forces and travel which correspond to the aircraft.

h. Instructor controls and seat.

i. At least a night and dusk visual system with at least a 75° horizontal by 30° vertical field of view for each pilot station.

j. A motion system with at least 6 DOF.

Level D Flight Simulator

Functional Description

a. Systems representations, switches, and controls which are required by the type design of the aircraft and by the user's approved training program.

b. Systems which respond appropriately and accurately to the switches and controls of the aircraft being simulated.

c. Full-scale replication of the cockpit of the aircraft being simulated.

d. Correct simulation of the aerodynamic characteristics including ground effect, and ground dynamic characteristics of the aircraft being simulated.

e. Correct simulation of selected environmental affected aerodynamic and ground dynamic characteristics of the aircraft being simulated considering the full range of its flight envelope in all approved configurations.

d. Control forces, dynamic, and travel which correspond to the aircraft instructor controls and seat.

e. A daylight, dusk, and night visual system with at least a 75° horizontal by 30° vertical field of view for each pilot station.

f. A motion system with at least 6 DOF.

2.2 AIRPLANE FLIGHT TRAINING DEVICE.

An airplane flight training device is a full-scale replica of an airplane's instruments, equipment, panels, and controls in an open flight deck area or an enclosed airplane cockpit. Flight training devices also include the assemblage of equipment and computer software programs necessary to represent the airplane in ground and flight conditions to the extent of the systems installed in the device. A force (motion) cueing or visual system is not required. It must meet the criteria outlined in FAA Advisory Circular, FAA-AC-120-45A, as amended in February 1992, for a specific flight training device level.

In coordination with various entities within the aviation industry, the FAA has defined seven levels of flight training devices, Level 1 through Level 7. Level 1 is currently reserved. Levels 2 and 3 are generic in that they are representative of no specific airplane cockpit and do not require reference to a specific airplane. Levels 4 through 7 represent a specific cockpit for the airplane represented. Within a specific category, each higher level of flight training device is

progressively more complex. Because of the increase in complexity and more demanding standards when progressing from Level 2 to Level 7, there is a continuum of technical capabilities across those levels. For a more detailed description of the different levels of flight training devices, a table of minimum standards (from FAA-AC-120-45A) for each level is presented in appendix A.

2.3 COMPUTER-BASED SIMULATION DEVICE.

A computer-based simulation device is a microcomputer that utilizes a cathode-ray tube (CRT) display, keyboard, and joysticks to simulate the operational aspects of the flight deck environment. These simulation devices usually contain a rough model of aircraft dynamics, displays to represent cockpit instruments, and joysticks to control pitch, roll, and thrust. Also, a keyboard is used to control avionics, aircraft configuration (gear, flaps, and spoilers), and subsystems (electrical, hydraulic, etc.). Ideally, these computer-based simulation devices will permit systematic interaction between subject and device, provide appropriate feedback, and automatically record a subject's performance.

The increase in utilization of computer-based simulation devices is a direct result of the advancements in microcomputer technology. New technology has made extremely fast, high-resolution graphics available at a low cost. A combination of these graphics capabilities and the sophisticated flight simulators now being designed for the microcomputer, has provided an inexpensive means of incorporating some of the activities performed by a pilot into the research setting (Shappell and Bartosh, 1991). The possibility of obtaining experimental control and a level of external validity for associated cognitive tasks is a benefit of microcomputer-simulation experimental research. Computer-based simulation devices range from simple interactive software representations of the out-the-window flight environment, to complex multidisplay devices capable of representing every component normally found within an aircraft cockpit. This level of variability, in terms of sophistication, has deterred any efforts to classify computer-based simulation devices in the same manner as was introduced for airplane simulators and airplane flight training devices.

2.4 SUMMARY.

The use of simulation for research is concerned with other issues in addition to physical realism, such as the level of realism perceived by the pilot (perceptual fidelity), and therefore can not be classified in accordance to the specifications outlined above. This lack of classification for research simulation devices has lead to confusion when specifying what type of simulation is necessary for a particular research task, and is the major reason for performing this analysis of fidelity requirements for simulation research.

The increased importance of the aforementioned simulation devices is due to a variety of factors, including cost and time savings that can be realized, the ability to reproduce and examine situations that would be unsafe using actual equipment, and the control and measurement of human-machine performance. Additional impetus has been provided by the tremendous technological advances in computer software and hardware capabilities being incorporated into these devices. These robust capabilities are being obtained at the expense of increased developmental, operational, and maintenance costs. This increased cost has caused flight simulator users to look closely at the simulator requirements necessary to effectively perform their tasks, and then invest enough resources to obtain a simulation device that meets their specified needs. The remainder of this document will discuss simulation requirements in terms of fidelity and how to determine what requirements are necessary for a specific task.

3. SIMULATION FIDELITY.

The concept of fidelity relates to the degree to which the characteristics of a flight simulator match those of the real airplane. The issue of simulator fidelity has been discussed and studied for over 30 years, and there is still no agreed upon single definition. During this time, the term has been used in a variety of ways and to refer to many different aspects of simulation. Attempts to make the term less vague have caused numbers of definitions to proliferate. Lane and Alluisi (1992) indicated that at least 22 different definitions have to be used in the literature to refer to different kinds of fidelity. A representative sample of the different kinds of fidelity includes such things as: equipment fidelity, environmental fidelity, psychological fidelity, task fidelity, physical fidelity, functional fidelity, and so on (Allen, Buffardi & Hays, 1991). Each of these kinds of fidelity could be appropriate for a particular application, but each are not individually applicable to overall aircraft simulation in general. A common thread, however, is that together they imply at least two major features or dimensions along which these simulated devices may differ from actual equipment.

These two features, as defined by the Advisory Group for Aerospace Research & Desi (AGARD) in 1980, represent the division of a simulator into two classes depending on the nature of the cues they provide.

a. Equipment cues provide a duplication of the appearance and feel of the operational equipment (the aircraft), i.e., the static and internal dynamic characteristics such as the size, shape, location, and color of controls and displays, including controller force and displacement characteristics.

b. Environment cues provide a duplication of environment and motion through the environment.

Fidelity is then a function of the degree to which the equipment and environmental cues relate to those of the real airplane. A distinction between the real cues, measured objectively, and the cues the pilot subjectively experiences, provides the following definitions for two types of fidelity (AGARD, 1980):

a. Objective Fidelity provides an engineering standard and is the degree to which a simulator would be observed to reproduce its real-life counterpart aircraft, in flight, if its form, substance, and behavior were sensed and recorded by a nonphysiological instrumentation system onboard the simulator. By including both equipment and environmental cues, this definition can encompass all pertinent dynamic cue timing and synchronization aspects of simulator fidelity.

b. Perceptual Fidelity provides a psychological/ physiological standard and is the degree to which the flight crew subjectively perceives the simulator to reproduce its real-life counterpart aircraft, in flight, in the operational task situation. The requirement that the operational equipment be considered in the context of the task situation ensures that not only cue timing and synchronization, but also cue priority effects, are taken into account.

Among the various categories of simulators, there is a tradeoff between equipment and environmental cue fidelity required. The physical correspondence between simulator and airplane in terms of cockpit layout, flight instruments, controls, etc., for training simulators should result in high equipment cue fidelity to advocate a high degree of transfer of training to the operational environment. On the other hand, research and development simulators should place more emphasis on high environmental cue fidelity. Environmental cues, by definition, provide duplication of the operational aircraft environment and motion, and thus will result in a higher degree of realism being experienced by the subjects. This perceived realism will result in subject performance more closely matching that which would occur in the real world. Figure 1 shows the requirements for equipment and environmental cue fidelity (AGARD, 1980).

Within the types of simulators indicated in figure 1, the levels of fidelity can vary greatly. For example, having cockpit crew coordination as the simulation task, a work station can be defined as a relatively low fidelity research simulator. Yet, another research simulator, such as those found at the Crew Station Research and Development Facility (CRSDF) located at NASA-Ames, certainly have a higher level of fidelity for evaluating the same task. Thus, for a specified research task, the user must be able to determine fidelity requirements. Failure to properly determine these requirements can result in (1) unsatisfactory results due to lack of fidelity, or (2) satisfactory results but at premium cost (suboptimization)

(Prasad et al., 1991). The problem now is how to define specific fidelity requirements for a simulation task.

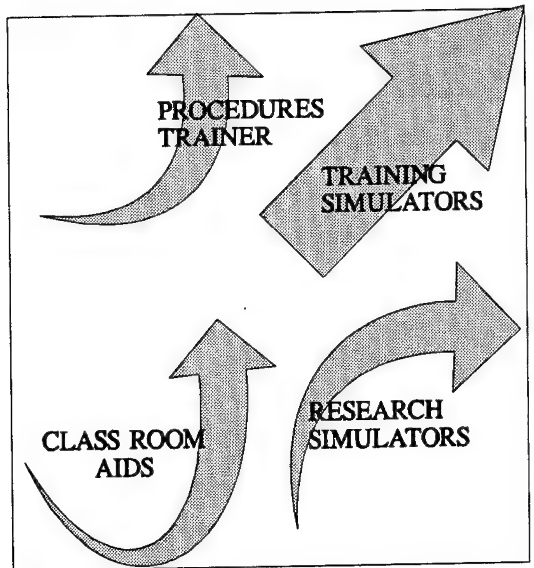

FIGURE 1. REQUIREMENT FOR EQUIPMENT AND ENVIRONMENTAL CUE FIDELITY (FROM AGARD, 1980)

3.1 FIDELITY DRIVERS.

The previous section discussed the concept of simulator fidelity and introduced its two most important components; objective and perceptual fidelity. Also, emphasis was put on the need to specify fidelity requirements. These requirements can be obtained by basing decisions on the configuration of the simulation system and the systematic rational examination of how the specific simulation is to be used (Lane & Alluisi, 1992). In that context, generalities about the pros and cons of high and low fidelity are not very helpful. Therefore, Lane and Alluisi (1992), developed four key dimensions or fidelity drivers to be used for the examination of simulation requirements. The four key fidelity drivers are identified and discussed below.

a. Mission(s) or Mission Segment to be Simulated - For realistic practice or evaluations to occur, the system must be used to perform some mission. A researcher may wish to simulate all mission phases or (frequently) only selected segments of a mission. The segments that are included in the simulation will dictate the specific tasks to be performed by the operator, the system components involved in performing these tasks, and thus the simulation components on which fidelity should be focused.

b. Objectives of the Simulation - A simulation is intended (1) to provide practice on specific skills, (2) to reinforce

acquisition and use of job-relevant knowledge, or (3) to evaluate a system or a new concept. These potential objectives can be described in terms of broad classes of basic operator activities that the simulation does or does not need to support. The fidelity required to meet specific objectives would be based on the extent to which each of the identified activities that occur within a mission segment must be supported by the simulation, and in what detail.

c. Fidelity Dimensions - The dimensions on which fidelity can be examined and evaluated can be grouped into three general classes: there are dimensions that show and describe the attributes of (1) the simulator, (2) the operator, and (3) the processes or events external to the simulator itself. The first class of attributes describes the simulated system itself, and the fidelity concerns are those that address the operator's equipment and its immediate environment--the look and feel that are a result of the physical, sensory, and perceptual variables employed. The second class of attributes are drivers that determine the specific tasks to be performed by the operator and the task loading under which the operator will work. These drivers are external to the system--what the operator does in the simulation is determined by how the simulated system is used. The third class of fidelity attributes are concerned with the external processes that generally arise from the dynamics of system participation in a variety of interactive events. Each of these attributes and characteristics defines a dimension of fidelity, and each requires decisions about the level of fidelity at which that attribute will be represented for a component of the simulation within the context defined by the missions and objectives of the simulation.

d. Simulation Components - The execution of simulation requires the presence of numerous individual components. These components are subdivided into local and global sets. Local components are part of the simulator and its immediate environment; they have roughly the same characteristics as the three classes of fidelity dimensions defined above. Global components are defined by the external processes and environments with which the local components interact. The importance of breaking down a simulation into its building blocks is that it is about these individual components that fidelity requirement decisions must be made.

These four drivers of fidelity constitute four dimensions on which any given simulation can be analyzed (Lane & Alluisi, 1992). The ultimate objective is to determine, for each component, on each fidelity dimension, the degree of fidelity required to support the intended uses of the simulation.

3.2 FIDELITY OF SIMULATION DEVICE SUBSYSTEMS.

The basic type of characteristics that drive simulator fidelity requirements have been outlined. However, definitions still do

not exist for the specific physical components of a simulator to analyze when determining fidelity requirements. Prasad et al., (1991) performed a survey of simulation devices and existing technologies and determined that there are generally ten subsystems, shown in table 1., which adequately describe a given simulator. Table 2 describes fidelity characteristics.

TABLE 1. SIMULATOR SUBSYSTEMS

(1) Cockpit	(6) Environment
(2) Audio	(7) Ground Handling
(3) Motion	(8) Mission Equipment
(4) Control System	(9) System Latency
(5) Math Model	(10) Visual

TABLE 2. LEVELS OF FIDELITY CHARACTERISTICS FOR SIMULATOR SUBSYSTEMS

SIMULATOR SUBSYSTEM	FIDELITY CHARACTERISTICS
(1) Cockpit/Crew Station	- none - simulated/generic type instruments - partially simulated cockpit - full up crew station
(2) Audio	- none - significant cockpit sounds - incidental sounds (precip., etc...) - realistic
(3) Motion	- none - 2DOF (pitch and roll) - 3DOF (pitch, roll, and yaw) - 6DOF
(4) Control System	- no force feel - constant force (spring/damper) - partial duplication of actual force - complete duplication
(5) Mathematical Model	- none - 3 DOF - 6 DOF - 6 DOF with rotor
(6) Environment	- clean air - discrete gusts - first order filtered turbulence - rotationally sampled turbulence
(7) Ground Handling	- no gear - rigid gear - simplified gear model - comprehensive
(8) Mission Equipment	- none - communication only - communication/navigation only - complete
(9) System Latency	- non real time (off line) - significant delay - minimal delay - real time
(10) Visual	<u>field of view</u> / <u>dynamic range</u> / <u>detail</u> workstation / day / low 75°horiz/35°vert / dusk / medium 90°horiz/40°vert / haze/fog / high wider / night / very high

For each subsystem, it is possible to associate a level of objective fidelity with the degree of equipment/software sophistication. For example, a simulator with day, night, and dusk visual capability with a wide field of view can be associated with high fidelity, while a simulator with just night visual capability can be associated with low fidelity. This association between fidelity and the subsystems defines fidelity characteristics; this can provide the necessary information for determining actual simulator characteristics needed to obtain a certain level of fidelity. Listed below are the fidelity characteristics (rank order; none to high) of the simulator subsystems that span the spectrum of fidelity (Prasad et al., 1991).

Because of the extensive use of flight simulators as both training and engineering evaluation devices, considerable effort has been devoted to determining the differences that exist between the simulation and in-flight environment. The information provided in the table gives a description of simulator fidelity and how the simulator components vary in levels of fidelity.

4. RESEARCH SIMULATOR FIDELITY REQUIREMENTS.

Up to this point, this document has introduced the various types of aviation simulation research devices and described the concept of simulator fidelity. This information can be used to determine how to manipulate simulator fidelity and how various simulator characteristics affect fidelity, but no recommendations for simulator fidelity requirements necessary to achieve a desired research goal have been introduced. This section will examine general fidelity requirements for experimental simulation research.

The essential feature of simulator experimental investigations is to introduce the pilots into a closed loop control situation, so that account is taken of their capabilities and limitations regarding the performance measure being evaluated. The expectation is that within the bounds of the experimental conditions, behavior in the simulator will match their behavior in the flight situation. Hence, the primary goal for a flight simulation researcher is to produce experimental conditions that elicit behavior that would occur under similar circumstances in the real world. The ultimate consideration is performance in the real world (Orlady, Hennessy, Obermayer, Vreuls & Murphy, 1988). This experimental construct for human factors research was alluded to by David Meister (1985) when he wrote:

> ...the purpose of ergonomic/human factors is to describe, analyze, measure, predict, and control the real world of systems functioning operationally (i.e., not under experimental control).

This statement results in further direction for human factors researchers, again in the words of Meister (1985):

...in consequence, the ideal environment in which to gather data is the operational environment. It may be necessary for various reasons to measure in some environment other than the real world, such as a laboratory or a simulator, but in such cases the conclusions derived from the data must be verified in the operational environment.

Meister's comments must always be considered during the determination of fidelity requirements for simulated research. Regardless of the level of fidelity and how accurately it was determined to meet the goals of the research, no simulator evaluation can completely duplicate the experience in the real world. Therefore, any results should be verified operationally before definite conclusions can be made.

4.1 DETERMINING FIDELITY REQUIREMENTS.

Fidelity, as defined earlier, is a multifaceted concept and is dependent on a variety of different simulator components. Also, fidelity is presently a metric-free construct with no agreed upon measurement scale on which the fidelity of a specific simulation can be located and assigned a numerical value (Lane & Alluisi, 1992). Furthermore, the requirements for fidelity change from one research effort to another, depending on what type of experimental study (part-task, full-mission, etc.) is being implemented or the types of measures being examined. These aspects of simulator fidelity support the general claim within the simulation community that fidelity requirements cannot be determined in general for various types of simulations and that they are dependent on the specific objective the simulation is intended to accomplish. If decision making skills and tactics are being evaluated, then high fidelity in vehicle handling characteristics are not critical. On the other hand, if primary interest is in the examination of manual-control skills, the answer is obviously different.

When planning human factors research, the required characteristics and features of the research vehicle are prominent issues of consideration in the goal of choosing the right simulator for the planned research investigation. Orlady et al., (1988) specified two principal factors in determining the choice of research vehicle (1) the type of research required by the problem, and (2) knowledge of the factors that influence the behavioral processes of interest. The type of research dictates the level of representation that the research vehicle must have. Knowledge of the factors which influence the behavioral processes determine how comprehensively the research vehicle must represent an operational system and its associated situational condition. Together, these features are commonly thought of as the fidelity of the research vehicle.

Practical, as well as scientific, considerations help determine the characteristics of a simulator used for research. In general, high fidelity representations of real-world situations

incur costs that are proportional to the comprehensiveness and complexity of the research project. Hence, a conflict arises between the real-world complexity of the operational tasks and the need for economy of the research effort. A second conflict arises between the need to elicit behavior that is equivalent to the real world, and the need to have experimental control to minimize variability necessary to make reliable and statistically significant conclusions. The goal of a simulation experiment design methodology is to determine a reasonable balance between these conflicting experimental demands.

Advancements in simulation technology are enabling nearly realistic environments to be utilized in experimental research. These accomplishments are providing continuing support towards the historical goal of designing a simulator to be equivalent to an actual aircraft. The view expressed by many in the simulation community is that the usefulness of a simulator should only be equated to its degree of realism. For research, the basic assumption is that the more faithful the simulation of real-world stimuli, the interfaces between individual crew members, the systems they control, and the systems that influence and regulate their behavior, the more likely it is that the behavior achieved in the experiment will be the behavior that would be produced under similar circumstances in the operational environment (Orlady et al., 1988).

A high level of fidelity has another advantage when used in research simulations. It increases the face validity of the experiment in the eyes of both the participants in the experiment and in the potential users of the research (Orlady et al., 1988). Face validity, or an apparent high level of real-world representation, in a simulation will allow the users in the aviation community to have more confidence in the experimental results.

When considering levels of fidelity for research it is often assumed that high fidelity is never a disadvantage, as is apparent in the philosophy stated by O'Hare and Roscoe (1990) as: "If you're not sure what's important, play safe and buy the most fidelity possible; surely something will work." There are, however, research as well as practical reasons not always to strive for maximum fidelity. In general, high fidelity implies a comprehensive representation of the real world. Furthermore, it provides an opportunity for unknown, extraneous factors to influence behavior, and gives subjects an opportunity to choose behavioral alternatives that may be beyond the research scope of interest. These potential consequences of high fidelity simulation contradict the two basic principles of behavioral research, as stated by Orlady et al., 1988, which are (1) maintain control of the research situation, and (2) to account for the factors which influenced the observed behavior. Unnecessarily high levels of fidelity can complicate the study and hinder the researcher's ability to investigate a specific research issue. The effects of high fidelity can often show up

as variability in the data and reduce the sensitivity of the performance measures as well as the reliability of their values.

However, it over simplifies the issue to say that a simulation should have all, but no more than, those characteristics that directly affect the behavior being examined. This is an ideal goal, but one that rarely can be achieved. Researchers too often include irrelevant capabilities into a simulation in an effort to increase fidelity. Attention should be given to maintaining control of the experimental situation, and the variability in subject behavior and performance that might result because of the presence of extraneous factors.

In conclusion, the concept of simulation fidelity, although in widespread use, is difficult to quantify, especially for research simulators. Additionally, the amount of research available that investigates fidelity requirements for research simulators is not abundant, and no real guidelines have ever been agreed upon by simulator researchers. Given this lack of significant research in the area and no generally accepted consensus, it is difficult to determine specific fidelity requirements for research applications. To reiterate, simulation fidelity requirements are dependent specifically on what the simulator is to be used for.

5. HUMAN FACTORS RESEARCH FIDELITY CONCERNS.

Simulation researchers are faced with the many problems, considerations, and conflicting issues relating to the determination of fidelity requirements for a simulation research effort. As mentioned throughout this document, fidelity is a multivariant construct with no consensus among researchers of a single index of measurement or definition. Furthermore, the associated benefits of using both high and low levels of fidelity for aviation experimental research has been shown. Given the degree of differences and difficulties relating to simulator fidelity, specific guidelines for various types of experimental research are not presently available. However, general conclusions can be made regarding how varying levels of fidelity can effect the outcome of different types of experiments.

This section will define the major types of experimental research studies performed in simulators, and introduce the fidelity concerns associated with each. Also, the types of performance measures that can be reliably investigated in research simulations are discussed. Finally, recommendations based on the information provided herein are given for specific types of simulation devices that can be used for various research objectives.

Before embarking on this introduction and discussion of experimental study types and their respective fidelity concerns, a general assumption of fidelity for research simulators must be presented. Research simulators as a whole demand high levels of fidelity due to their overall objective of observing behavior.

Research needs are more rigorous and fidelity requirements are more strict so that researchers can observe behavior as close to the operational environment as possible. Deviations from the behavior being studied provide variance that can confound analysis. This high level of fidelity assumption is not all encompassing for research simulators. There are, as mentioned earlier, several instances where a high level of fidelity can be a disadvantage, and these research issues will be discussed later. But, the majority of information regarding fidelity requirements for experimental research studies addresses issues pertaining to high fidelity research devices.

5.1 SIMULATION RESEARCH STUDY TYPES.

Experimental research studies performed using a simulation device generally fall into two categories, full-mission and part-task. Full-mission studies examine behavior in the full context of the aviation environment, while part-task studies concentrate on the behavior relating to a specific task or function. Within these two categories there are distinct study types that are distinguished by the complexity of their objectives or the type of simulation device used for investigation.

Full-Mission Studies

The basic idea of full-mission relates to performing a research study with the most realistic simulation possible. Full-mission simulation, as stated by Orlady et al., (1988), includes all of the stimuli presented to the flight crew. It includes the aircraft cockpit, visual and motion cues, aircraft flight dynamics, all of the aircraft subsystems, the flight environment (including air traffic control (ATC), weather, and other air or ground vehicular traffic), the cabin crew, and all ancillary flight services (such as dispatch, ramp passenger services, and maintenance).

A full-mission simulation study can involve numerous simulators in the same study environment connected together over a network, known as an Interactive Mission Scenario (Prasad et al., 1991). Also, a full-mission simulation that examines behavior over an entire flight from preflight checklist to parking at the gate is considered an end-to-end simulation experimental study.

Given the above definition of full-mission simulation and the types of experimental studies mentioned that utilize this technique, it can be accurately stated that only airplane simulators, as defined in section 2., can be used for full-mission simulation applications. The airplane simulators are the only simulation devices that specify visual and motion characteristics by definition, and these capabilities are definitely necessary when conducting full-mission simulation research. The overall fidelity associated with the full-mission simulation is related to what level (A, B, C, or D) of airplane simulators is used in the study. A main fidelity issue of

concern in full-mission simulation is the pilot subjects desire for scenario fidelity. Pilots generally do not accept deviations from operational practice unless it is specified at the beginning of the simulation. Pilots experiencing negative user acceptance cues are more likely not to elicit the same behavior as they might in the real world.

The full-mission simulation type of devices can be used to investigate cognitive tasks in the context of the multitask, complex operation of flying an airplane. Also, much of the research performed using full-mission simulation focuses on cockpit instrumentation, crew procedures, and workload measurement. Topics of investigation include how decisions made in the cockpit are affected by environmental and hardware difficulties as well as by the availability of information from ATC and other aircraft, how errors are made, and the effects of automation, fatigue, and advanced instrumentation of human performance (Jones, Hennessy, and Deutsch, 1985).

Orlady et al., (1988) indicated four principal reasons for doing full-mission simulation:

1. To resolve a collection of related problems - if there is a series of part-task evaluations planned, it may be more economical to group them together in a comprehensive study.

2. When the focus of interest is on long duration or infrequent events and effects - behavior under fatigue and responses to rare emergencies as a function of time are obvious examples.

3. Subtle interactions may influence the behavior of interest - results of a crew coordination, vigilance, judgment, or resource management study are likely to be adversely affected if the simulation is not physically comprehensive and realistic, or if scenario is too short.

4. To evaluate performance of people and/or equipment that occurs during a series of transitions from one flight phase of operation to another.

These capabilities of full-mission simulation show the importance this technique has within human factors simulation research. However, there may be types of studies which can be accomplished more efficiently using other research methods with lower-fidelity simulation devices. The problem is that researchers are unsure about the level of fidelity necessary, and too often elect the safer route of full-mission simulation with high fidelity.

Part-Task Studies

The concept of a part-task study is to investigate a performance measure in response to a specific manipulated task or function. Part-task simulation is characterized by a functional

representation of a specific subsystem. These types of simulation devices isolate a single critical function for evaluation in terms of pilot behavior. For example, a part-task study may only evaluate specific instruments, displays, operational procedures, or controls found in the cockpit. The benefit of part-task simulation is derived from the view that the evaluation of smaller component tasks is more acceptable for experimental testing and statistical analysis and more objective information regarding performance can be obtained. However, what part-task simulation may gain in experimental control, it lacks in external validity, i.e., accurate representation of the real world.

Part-task simulation is appropriate for research when there is no reason to suspect behavior will be influenced by secondary contextual circumstances (Orlady et al., 1988). Basically, studies looking at human performance on a specific individual task (reaction time, accuracy, etc.), or functional problems inherent to a task or condition can be evaluated using part-task simulation. Furthermore, as stated earlier, extraneous factors may add unwanted variance to the particular problem being researched.

Devices used for part-task studies range from cardboard cutouts representing cockpit displays, to the most sophisticated flight training device. Also, the technology advancements in microcomputer graphics is resulting in an increased utilization for part-task research. Computer-based simulators can present real-life replicas of cockpit displays and allow subjects to interact with the cockpit as they would during normal operations. The fidelity characteristics of part-task simulations are related to the graphics capability of the microcomputer and the level of flight training device 1-7, as defined earlier, being used in the research. Some part-task research requires only minimal real-world fidelity and limited, but highly specialized expertise with regards to subject capabilities. Other kinds of part-task research might demand only a simple scenario to investigate a fundamental decision process, but little in the way of a real cockpit or visual system.

5.2 SIMULATION RESEARCH FIDELITY RECOMMENDATIONS.

As mentioned throughout this document, there are no specific guidelines for determining simulator fidelity requirements for human factors research. Fidelity is dependent on the individual goal and area of investigation for a research study. However, general capabilities and limitations of various simulation devices and their associated levels of fidelity can be summarized. This section combines the pertinent information found in this analysis regarding research simulation device specifications, fidelity requirements for research, and the characteristics of the different types of experimental research simulation techniques. This information is used to summarize

some general recommendations concerning the levels of fidelity necessary to properly conduct human factors simulation research.

Full-Mission Studies

When investigating proper fidelity levels for full-mission simulation studies a researcher would generally desire the highest level of fidelity available. Full-mission simulation, by definition, requires all stimuli present in the operational environment and it has been shown that the more the simulator characteristics match those of the real world, the more subject behavior matches actual behavior that would occur operationally.

Full-mission simulation can be used to investigate cognitive tasks in the context of the multitask, complex operation of flying an airplane. Specifically, full-mission simulation human factors research focuses on cockpit instrumentation, crew procedures, and workload measurement. Furthermore, topics concerning how decisions made in the cockpit are affected by environmental and hardware difficulties, how errors are made, and the effects of automation, fatigue, and advanced instrumentation on human performance can be investigated using full-mission simulation. Additional uses of and reasons for utilizing full-mission simulation were mentioned earlier.

The restriction that full-mission simulation only be performed using flight simulators narrows the issue of determining an adequate simulation device, but there still is the varying level of fidelity among the four levels of airplane simulators. Full-mission simulation can be performed in any level simulator A through D, given their respective characteristics and capabilities. However, as the level of simulator fidelity increases, there is also an increase in the capital investment required to perform the research. Therefore, a tradeoff exists between the desire to perform research as economically as possible, and the need to obtain valid results that represent behavior in the operational environment. In any event, the higher the level of simulator fidelity utilized in a full-mission simulation research study, the more accurately a researcher can make generalizations about behavior in the real world.

This rule of thumb for full-mission simulation research studies is a general recommendation associated with the utilization of different levels of simulators. Specific guidelines for minimum fidelity requirements that may vary from one level of simulator to another depending on the objective of the full-mission simulation research cannot be accurately determined, as alluded to throughout this document. The only guideline available for full-mission simulation is that the research results become more generalizable as the level of fidelity increases.

Part-Task Studies

Determining of fidelity requirements for part-task simulations is more difficult and therefore more complicated than the general rule presented for full-mission simulations. In general, part-task studies investigate a dependent performance measure in response to a specific manipulated task. Consequently, part-task simulations are appropriate to measure performance on a specific task when no other conditions are believed to influence behavior. For example, if a researcher is interested in measuring human performance on an individual dependent task such as reaction time or accuracy, a part-task study would allow the behavior to be measured individually with no other conflicting factors influencing behavior.

Part-task simulations can utilize a wide variety of simulation devices such as: microcomputer simulation devices, low-fidelity desktop training devices, and high fidelity airplane flight training devices. This wide range of fidelity devices complicates the issue of determining specific requirements for part-task simulation fidelity. The utilization of too much fidelity can result in unwanted variance associated to the behavior being examined. On the other hand, if the simulation does not represent the context in which the specific task is to be investigated, due to a low level of fidelity, the behavior examined may not be exactly that for which the research was intended. Hence, fidelity requirements for part-task simulations cannot be determined in general. The requirements must be determined on a case-by-case basis depending on the objectives of the research.

If a researcher is interested in a baseline human performance measure such as rate of errors or reaction time, or in comparing display formats for user-acceptance, rudimentary flight training devices and computer-based simulation devices could be used to examine behavior. These types of part-task studies do not require the behavior to be measured in the full airplane context. Conversely, a high fidelity flight training device would be necessary to evaluate operational procedures such as preflight or approach checklists for a specific airplane. To perform these procedures, subject pilots would need a complete replication of the specified aircraft's cockpit. These capabilities are only found in the most sophisticated flight training devices, levels (4-7) as defined earlier.

Other examples, such as the one just mentioned, could be presented to indicate specific types of research that could be adequately performed in the various part-task simulation devices. However, no general guidelines are applicable for the full range of part-task simulations. Each individual study has its own characteristics and objectives and therefore its own fidelity requirements based on the context that a specific behavior must be measured within.

The aforementioned recommendations for part-task simulation fidelity requirements were not very specific. As the main problems associated with simulation fidelity requirements mentioned in this document were brought to the forefront for part-task research. Specifically, the fact that fidelity defies simple description or measurement and thus levels of required fidelity can not be determined in general for various types of part-task simulation research.

Conclusions

Simulation fidelity is an obscure concept that is being thrust onto the simulation community as a way to measure a simulation device's effectiveness for human factors research. To date, no consensus on just what exactly fidelity is, or how it affects simulation research efforts has been agreed upon. Also, there is even more discrepancy regarding how to determine fidelity requirements for specific types of human factors research. This document analyzed the latest research pertaining to simulation research fidelity requirements and made general recommendations as to the requirements necessary when performing various types of human factors simulation research.

In the past few years simulation has become more acceptable for research due to technology advancements enabling nearly realistic levels of simulator fidelity. This trend is likely to increase, given the steady improvements in all aspects of simulation. A well-designed research simulation project is cost-effective when compared to most other ways of achieving the same objectives, such as flight test. However, as the use of simulation for research increases, more specific guidelines and requirements for fidelity are necessary to ensure that the simulation devices are being used effectively to meet the objectives of the specified research.

6. FUTURE RESEARCH AND RECOMMENDATIONS.

As shown in this analysis, fidelity is an ambiguous concept not clearly defined or agreed upon in the simulation research community. The benefits of better understanding fidelity and its requirements for simulation research are numerous. Specifically, the ability to determine the exact amount of fidelity necessary for an individual research objective, and then be able to choose the correct simulation device for the desired level of fidelity would reduce the chance of conducting research with an inadequate level of simulation. To reiterate, current decisions on simulation devices for research are resulting in unnecessary costs and extraneous factors negatively effecting results when too much fidelity is utilized, and behaviors that do not represent real-life are providing insufficient results when not enough fidelity is incorporated.

Presently, there are no guidelines for determining fidelity requirements for various simulation research applications.

Furthermore, there is no consensus on the effects varying levels of fidelity have on research results, or for the amount of fidelity necessary to elicit useful evaluations of behavior. To provide answers to these questions and begin to have a better understanding of simulator fidelity in its entirety, several topics for future research are recommended.

One area of fidelity research that needs more attention is the determination of a quantitative method of defining fidelity. As mentioned earlier, fidelity is a metric-free subjective value perceived differently from one person to the next. Variations in the fidelity of individual components, as well as the simulator as a whole need to have a universal index for comparison. This index could be used to determine a specific value of fidelity necessary for a research objective, and also give a method of comparing one simulator to another based on level of fidelity.

Further research is also needed for the determination of specific criteria for classifying simulators in terms of overall fidelity. Currently the Federal Aviation Administration (FAA) categorizes aircraft simulation devices in terms of objective (engineering) fidelity, as illustrated in Advisory Circulars No. 120-40B and 120-45A. Simulation devices, for research especially, need to be categorized in terms of their perceptual fidelity as well. This would allow a researcher with specific fidelity requirements to choose a simulator that is appropriate. Simulator classification by fidelity sets a basis from which the user community can identify the specific simulation device that is optimized for their needs (Prasad et al., 1991).

Also, further analysis and examination of human factors simulation studies will provide guidance for fidelity issues that need to be considered in future simulation studies. Upon completion of a research study, practitioners could analyze the effects that the level of fidelity utilized had on the desired outcome. Study specifics such as type of simulator, measures evaluated, fidelity characteristics and a general description of the experimental study from subject and observer comments would be obtained. The information could be stored in a database and be available for future researchers to access when addressing fidelity concerns for their own human factors simulation research.

Lastly, a process by which to determine what type of simulation research to conduct, full-mission or part-task, and the type of simulation device to utilize for a specific research evaluation, is needed for researchers to obtain the most benefit from research conducted using simulation. The experimental factors included in the following checklist provide a list of issues to be examined when determining the type of experimental simulation device, and level of sophistication, for a particular study.

Upon addressing these issues of concern for simulation research, a researcher can then match the specified needs with the

characteristics and capabilities found in the different study types to determine which will result in the most appropriate evaluation for the planned research. For future FAA Technical Center simulation research, it is recommended that this process be used to determine simulator sophistication requirements. A committee of experts made up of Crew System Ergonomics Information Analysis Center (CSERIAC) and FAA personnel could objectively determine these requirements based on a specific study's characteristics, as determined by addressing issues listed in the checklist below.

Checklist of Experimental Factors to Consider for Simulation Research
GENERAL
- Time - Cost - Aircraft (modeVseries) - Systems to be tested - Statistical Power needed - External Factors of Interest
EXPERIMENTAL METHODOLOGY
- Research Objective - Variables of Interest - Behavior of Interest - Physiological Factors to be stimulated - Psychological Factors to be stimulated - Procedures/Skills to be tested

The use of simulators for research is increasing as technology enhancements improve their capabilities. A better understanding of the concept of fidelity is necessary to assure that simulation devices are utilized correctly for human factors research. The recommendations presented herein for simulator fidelity issues to address in the future will start providing answers to the questions and concerns expressed throughout this document.

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APPENDIX A

FLIGHT TRAINING DEVICE MINIMUM STANDARDS AS SPECIFIED IN FAA-AC-120-45A

Table A. Flight Training Device Minimum Standards

GENERAL	LEVEL 1	2	3	4	5	6	7	Comments
a. A cockpit which will have actuation of controls and switches which replicate those in the airplane.			X			X	X	Level 3 must be representative of a single set of airplanes, and must have navigation controls, displays, and instrumentation as set out in FAR Section 91.33 for operation in accordance with instrument flight rules (IFR).
b. Instruments, equipment, panels, systems, and controls sufficient for the training/checking events to be accomplished must be located in a spatially correct open flight deck area. Actuation of these controls and switches must replicate those in the airplane.		X		X	X			Level 2 must be representative of a single set of airplanes. Levels 2 and 5 require simulated aerodynamic capability and control forces and travel sufficient to manually fly an instrument approach.
c. Daily preflight documentation.		X	X	X	X	X	X	
d. Lighting environment for panels and instruments must be sufficient for the operation being conducted.		X	X	X	X	X	X	Lighting must be as per airplane lighting for Level 7.
e. Circuit breakers should function accurately when they are involved in operating procedures or malfunctions requiring or involving flight crew response.		X	X	X	X	X	X	Must be properly located in Levels 6 and 7.
f. Effect of aerodynamic changes for various combinations of drag and thrust normally encountered in flight, including the effect of change in airplane attitude, thrust, drag, altitude, temperature, and configuration		X	X		X	X	X	Levels 3, 6, and 7 require additionally, the effects of gross weight and center of gravity.
g. Digital or analog computing of sufficient capacity to conduct complete operation of the device including its evaluation and testing.		X	X	X	X	X	X	
h. All relevant instrument indications involved in the simulation of the applicable airplane entirely automatic in response to control input.		X	X		X	X	X	
i. Navigation equipment corresponding to that installed in the replicated airplane with operation within the tolerances prescribed for the actual airborne equipment.		X	X		X	X	X	Levels 3, 6, and 7 must also include communication equipment (interphone and air/ground) corresponding to that installed in the replicated aircraft, and, if appropriate, to the operation being conducted, an oxygen mask microphone/communication system. Levels 2 and 5 need have operational only that navigation equipment sufficient to fly a non-precision instrument approach.

Table A. Flight Training Device Minimum Standards (cont'd)

GENERAL	LEVELS 1	2	3	4	5	6	7	Comments
j. Crewmember seats must afford the capability for the occupant to be able to achieve the design eye reference position for specific airplanes, or to approximate such a position for a generic set of airplanes.			X		X	X	X	Level 7 crewmember seats must accurately simulate those installed in the airplane.
k. In addition to the flight crew-member stations, suitable seating arrange-ments for an instructor/check airman and FAA inspector. These seats must provide adequate view of crewmember's panel(s).		X	X	X	X	X	X	These seats need not be a replica of an aircraft seat and can be as simple as an office chair placed in an appropriate position.
l. Installed system(s) must simulate the applicable airplane system operation, both on the ground and in flight. At least one airplane system must be represented. System(s) must be operative to the extent that applicable normal, abnormal, and emergency operating procedures included in the operator's training programs can be accomplished.		X	X	X	X	X	X	Levels 6 and 7 must simulate all applicable airplane flight, navigation, and systems operation. Level 3 must have flight and navigational controls, displays, and instrumentation for powered aircraft as set out in FAR Section 91.33 for IFR operation. Levels 2 and 5 must have functional flight and navigational controls, displays, and instrumentation.
m. Instructor controls that permit activation of normal, abnormal, and emergency conditions, as may be appropriate. Once activated, proper system operation must result from system management by the crew and not require input from the instructor controls.		X	X	X	X	X	X	
n. Control forces and control travel which correspond to that of the replicated airplane, or set of airplanes. Control forces should react in the same manner as in the airplane, or set of airplanes, under the same flight conditions.		X	X		X	X	X	Levels 2 and 5 need control forces and control travel only of sufficient precision to manually fly an instrument approach.
o. Significant cockpit sounds which result from pilot actions corresponding to those of the airplane.			X			X	X	
p. Sound of precipitation, windshield wipers, and other significant airplane noises precipitable to the pilot during normal, abnormal, or emergency operations, as may be appropriate.							X	Statement of Compliance.

Table A. Flight Training Device Minimum Standards (cont'd)

	LEVELS							
GENERAL	1	2	3	4	5	6	7	Comments
q. Aerodynamic modeling which, for airplanes issued an original type certificate after June 1980, includes low-altitude level-flight ground effect, Mach effect at high altitude, effects of airframe icing, normal dynamic thrust effect on control surfaces, aeroelastic representations, and representations of nonlinearities due to sideslip based on airplane flight test data provided by the manufacturer.							X	Statement of Compliance. Tests required. The statement must address ground effect, Mach effect, aeroelastic representations, and nonlinearities due to sideslip. Separate tests for thrust effects and demonstration of icing effects are required.
r. Control feel dynamics which replicate the airplane simulated. Initial and upgrade evaluation will include control free response (column, wheel, and pedal) measurements recorded at the controls. The measured responses must correspond to those of the airplane in takeoff, cruise and landing configurations. (1) For airplanes with irreversible control systems, measurements may be obtained on the ground if proper pilot static inputs are provided to represent conditions typical of those encountered in flight. Engineering validation or airplane manufacturer rationale will be submitted as justification to ground test or omit a configuration. (2) For flight training devices requiring static and dynamic tests at the controls, special test fixtures will not be required during initial evaluations if the operator's ATG shows both test fixture results and alternate test method results, such as computer data plots, which were obtained concurrently. Repeat of the alternate method during the initial evaluation may then satisfy this test requirement.							X	Statement of Compliance.
s. Aerodynamic and ground reaction modeling for the effects of reverse thrust on directional control.							X	Statement of Compliance. Tests required.
t. Timely permanent update of flight training device hardware and programming consistent with airplane modifications.		X	X	X	X	X	X	

Table A. Flight Training Device Minimum Standards (cont'd)

GENERAL	LEVELS 1	2	3	4	5	6	7	Comments
u. Visual system; if installed (not required).		X	X	X	X	X	X	Visual system standards set out in AC 120-40, as amended, for at least Level A simulators will be acceptable.
v. Motion system; if installed (not required).		X	X	X	X	X	X	Motion system standards set out in AC 120-40, as amended, for at least Level A simulators will be acceptable.